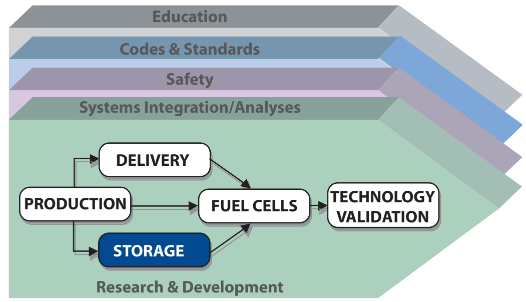
3.3 Hydrogen Storage



Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell power technologies in transportation, stationary, and portable applications. The Hydrogen Storage program element will focus primarily on the research and development of on-board vehicular hydrogen storage systems that will allow for a driving range of 300 miles or more. In addition, this program element will develop hydrogen storage systems for off-board applications such as the hydrogen delivery and refueling infrastructure, Power Parks, and vehicle interface technologies for the refueling of hydrogen storage systems on vehicles.

3.3.1 Technical Goal and Objectives

Goal

Develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications.

Objectives

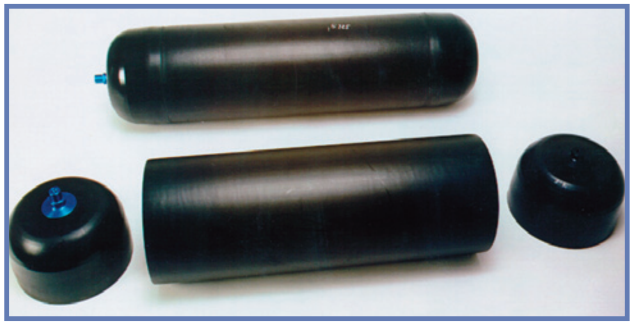
- By 2005, develop and verify on-board hydrogen storage systems achieving 1.5 kWh/kg (4.5 wt%), 1.2 kWh/L, and $6/kWh.
- By 2010, develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt%), 1.5 kWh/L, and $4/kWh.
- By 2015, develop and verify on-board hydrogen storage systems achieving 3kWh/kg (9 wt%), 2.7 kWh/L, and $2/kWh.
- By 2015, develop and verify low-cost, off-board hydrogen storage systems, as required for hydrogen infrastructure needs to support transportation, stationary and portable power markets.
- By 2015, develop and verify vehicle interface technologies for fueling on-board hydrogen storage systems.

3.3.2 Technical Approach

In most situations, on-board hydrogen storage systems are more challenging than off-board due to space, weight and cost limitations. Therefore, on-board hydrogen storage is the focus of the Hydrogen Storage program element. DOE is currently assessing the requirements for off-board hydrogen storage, and will initiate research and development activities of off-board technologies as appropriate. This will include hydrogen storage for stationary power systems, at vehicle fueling facilities, within the hydrogen delivery infrastructure at terminals and for surge capacity, and at hydrogen production facilities.

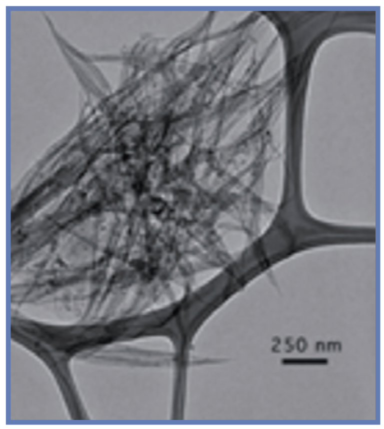
A series of workshops with scientists and engineers from universities, national laboratories, and industry has been held to identify the R&D priorities of the Hydrogen Storage program element. A "Think Tank" meeting, which included Nobel laureates and other award-winning scientists, was held to identify advanced material concepts and to develop an R&D strategy. Interactions with the DOE Office of Basic Energy Sciences are ongoing to define and coordinate the basic research activities for hydrogen storage materials.

Figure 3.3.1. Hydrogen storage tanks that improve tank gravimetric energy density, reduce hydrogen gas permeation through tank liners, and optimize tank overall design are under development.



Specific gravimetric, volumetric, and cost hydrogen storage targets have been developed for 2005, 2010, and 2015, as indicated in the objectives. Storage approaches that will be pursued to achieve these goals are compressed gas and liquid hydrogen tanks for near-term vehicles (2005), and reversible solid-state hydrogen storage materials, solid-state chemical storage, and advanced concepts for the longer term vehicle applications (2010–2015) (see Figures 3.3.1 and 3.3.2). Currently, hydrogen is stored both off-board and on-board concept vehicles as a high-pressure compressed gas or a cryogenic liquid.

Figure 3.3.2. Micrograph of carbon nanostructure, which can safely store high volumes of hydrogen and release it on demand - a promising storage option for the future.



Vehicle refueling connection devices for both compressed hydrogen gas tank storage and solid-state hydrogen storage systems will be designed, developed, tested, and qualified. Key aspects here will be safety, reliability, refueling time, and minimum complexity for the operator. In October 2002, the Society of Automotive Engineers (SAE) International issued a surface vehicle standard titled, "Compressed Hydrogen Surface Vehicle Refueling Connection Devices," and current activities include a companion standard dealing with the software requirements for the infrastructure-vehicle fueling interface. Validation of both the hardware and software aspects of this interface is an important activity in the near term. Supplying hydrogen to advanced on-board hydrogen storage systems may very well place new and more challenging requirements on the infrastructure-vehicle interface. As these systems are developed and demonstrated, refueling standards will evolve with them to maintain the safety, reliability, refueling time, and ease-of-use requirements.

The Hydrogen Storage program element will include on-going analysis to examine the cost and energy efficiency of the technologies developed, any changes in the system-level requirements that might alter the technical targets, and the progress of each technology development effort toward achieving the technical targets.

Funding for hydrogen storage R&D will be scaled down according to measurable progress—as technical and cost targets are met or missed, funding for particular technological approaches will be adjusted. When all performance, safety, cost targets are met, hydrogen storage R&D funding will end as appropriate. If specific performance issues remain at that time, R&D could be extended if the risk of the continued effort is justified by the potential benefit.

3.3.3 Programmatic Status

Current Activities

Table 3.3.1 summarizes the current activities ongoing in the Hydrogen Storage program element. For compressed hydrogen, lightweight composite tanks with high pressure ratings and conformability are being developed. Improved insulated pressure vessels for liquid hydrogen storage are also being investigated. In the complex metal hydrides, there is a broad research program for the alanates to determine their potential for hydrogen storage. Similarly carbon nanotubes are being explored to ascertain possible novel hydrogen uptake mechanisms. Finally, a testing and evaluation center is being established to develop standard test protocol and provide independent verification of hydrogen storage materials performance. Currently no projects in the program deal with chemical hydrides or off-board hydrogen storage. These will be initiated in FY 2004.

Table 3.3.1. Current Hydrogen Storage Activities

Technology	Organizations	Project Focus
Compressed Hydrogen Tanks	Quantum	10,000 psi Composite Tanks
	Johns Hopkins University, Lincoln Composites	Conformable Tanks
	Lawrence Livermore National Laboratory	Lightweight Composite Tanks
Liquid Hydrogen Tanks	Lawrence Livermore National Laboratory	Insulated Pressure Vessels
Complex Metal Hydrides	University of Hawaii	Alanates - Kinetics, Mechanisms
	Sandia National Laboratory - Livermore	Alanates - Kinetics, Mechanisms, Engineering
	United Technologies Research Center	Alanates - Cycle Life, System Engineering, Safety
Carbon	National Renewable Energy Laboratory	Nanotubes - Kinetics, Mechanism
Testing and Evaluation	Southwest Research Institute	Standard Test Protocol, Independent Test Facility

Technology Status (Demonstrations)

In the area of on-board hydrogen storage, the state-of-the-art is 5000- and 10,000-psi compressed tanks, and cryogenic liquid hydrogen tanks. Tanks have been certified worldwide according to ISO 11439 (Europe), NGV-2 (U.S.), and Reijikijun Betten (Iceland) standards, and approved by TUV (Germany) and KHK (Japan). They have been demonstrated in several prototype fuel cell vehicles and are commercially available at low production volumes. All-composite, 10,000-psi tanks have been developed and have demonstrated a 2.35 safety factor (23,500-psi burst pressure) as required by the European Integrated Hydrogen Project specifications. Liquid hydrogen tanks have also been demonstrated. A sodium borohydride system has been demonstrated in a concept vehicle. Off-board storage has been demonstrated at several hydrogen refueling stations in the U.S.

3.3.4 Technical Challenges

For transportation applications, the overarching technical challenge for hydrogen storage is how to store the necessary amount of hydrogen fuel required for conventional driving range (>300 miles), within the constraints of weight, volume, durability, efficiency, and total cost. Weight and volume requirements are greatly relaxed for off-board hydrogen storage compared to on-board; however, volume is an important consideration in many off-board installations where space is limited, especially at refueling stations. In addition, significant energy is required to compress or liquefy the hydrogen. These energy investments are strongly coupled to hydrogen production and distribution technolgies, and energy requirements must be minimized for the total production/delivery/storage system. Compression and liquefaction are discussed in the Hydrogen Delivery section of this plan (see Section 3.2). Cost is an important factor for off-board hydrogen storage, as for on-board storage, if these storage systems are to be competitive with conventional petroleum fuel storage or conventional energy storage (i.e., batteries).

Clearly, many important technical challenges for hydrogen storage must be resolved to meet the ultimate performance and safety targets. Costs must be reduced by a factor of almost ten for storage systems, and substantial improvements must be made in the weight and volume of these systems, for vehicle applications in particular. Durability over the performance lifetime of these systems must be verified and validated and acceptable refueling times must be achieved. Section 3.3.4.2 lists the specific technical barriers that must be resolved to achieve the performance targets. Section 3.3.5 describes the tasks that will be carried out to resolve the identified technical barriers.

3.3.4.1 Technical Targets

The technical performance targets for hydrogen storage systems are summarized in Table 3.3.2. Figures 3.3.3 and 3.3.4 show the status of current technologies relative to performance and cost targets, respectively. These targets are specifically for on-board vehicle storage systems and were established with the FreedomCAR Hydrogen Storage Technical Team, based on the following vehicle production volume assumptions:

- 2005: very low-volume demonstration
- 2010: suitable for large scale commercial production on a limited number of the least demanding platforms
- 2015: suitable for mass production of a full spectrum of vehicles

Based on the lower heating value (LHV) of hydrogen and a minimum 300-mile vehicle range, the targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. Targets for off-board storage and stationary fuel cell applications will be identified following a study to assess the storage needs for these applications.

Table 3.3.2. Technical Targets: DOE Hydrogen Storage System Targets[a, b, c]

Storage Parameter	Units	2005	2010	2015
Usable, specific-energy from H_2 (net useful energy/max system mass)[d]	kWh/kg ($kg\ H_2/kg$)	1.5 (0.045)	2 (0.06)	3 (0.09)
Usable energy density from H_2 (net useful energy/max system volume)	kWh/L ($kg\ H_2/L$)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost[e]	\$/kWh net (\$/kg H_2)	6 (200)	4 (133)	2 (67)
Fuel cost[f]	2001 US\$ gallon gasoline equivalent at pump	3	1.5	1.5
Operating ambient temperature[g] Cycle life (1/4 tank to full)[h]	°C Cycles	-20/50 (sun) 500	-30/50 (sun) 1000	-40/60 (sun) 1500
Cycle life variation[i]	% of mean (min) @ % confidence	N/A	90/90	99/90
Minimum and maximum delivery temperature of H_2 from tank	°C	-20/100	-30/100	-40/100
Minimum full flow	(g/sec)/kW	0.02	0.027	0.033
Minimum delivery pressure of H_2 from tank (FC=fuel cell, ICE=internal combustion engine)	Atm (abs)	2.5 FC 10 ICE	2.5 FC 35 ICE	2 FC 35 ICE
Transient response 10% to 90% and 90% to 0%[j]	Sec	0.5	0.5	0.5
Start time to full flow at 20°C	Sec	4	0.5	0.5
Start time to full flow at minimum ambient	Sec	8	4	2
Refueling rate[k]	kg H_2/min	0.5	1.5	2
Loss of useable hydrogen[l]	(g/hr)/kg H_2 stored	1	0.1	0.05
Permeation and leakage[m]	Scc/hr	Federal enclosed-area safety-standard		
Toxicity		Meets or exceeds applicable standards		
Safety		Meets or exceeds applicable standards		

[a] Based on the lower heating value of hydrogen and a minimum of 300-mile vehicle range; targets are for complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. System must be energy efficient - for reversible systems, greater than 90% energy efficient; for systems generated off-board, greater than 70% life-cycle efficiency. Useful hydrogen constants: 0.2778kWhr/MJ, ~33.3kWhr/gal gasoline equivalent, lower heating value=32.72 kWhkg.
[b] Unless otherwise indicated, all targets are for both internal combustion engine and for fuel cell use, based on the low likelihood of power-plant specific fuel being commercially viable.
[c] Vehicle production volume assumptions: 2005 – very low volume demonstration, 2010 – suitable for large scale commercial production on a limited number of the least demanding platforms, 2015 – suitable for mass production of a full spectrum of vehicles.
[d] Generally the 'full' mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.
[e] 2003 US\$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.
[f] Includes off-board costs such as liquefaction, compression, regeneration, etc; 2015 target based on H_2 production cost of \$1.50/gasoline gallon equivalent untaxed.
[g] Stated ambient temperature plus full solar load
[h] Equivalent to 100,000; 200,000; and 300,000 miles respectively.
[i] All targets must be achieved at end of life.
[j] At operating temperature.
[k] 2015 target is equivalent to 3-5 minutes refueling time.
[l] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.
[m] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces.

Figure 3.3.3. Status of current technologies relative to the key performance targets.

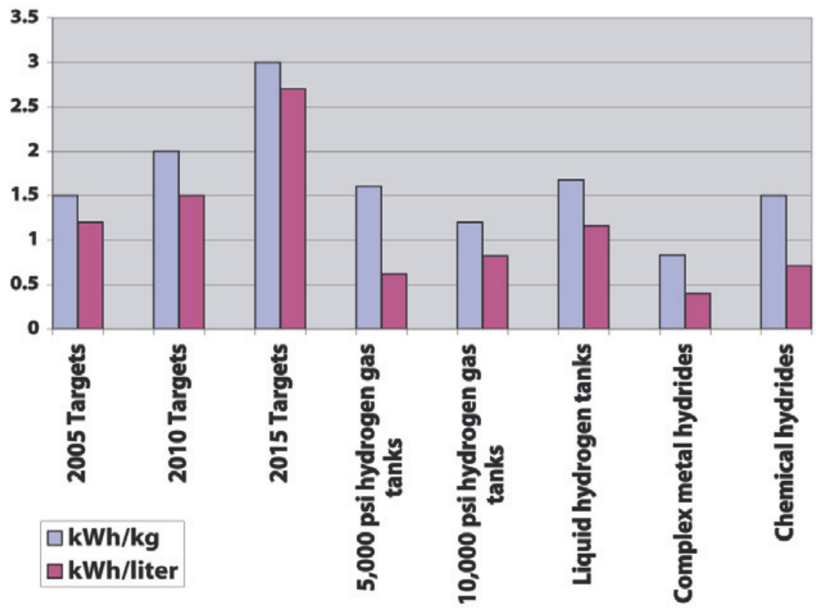
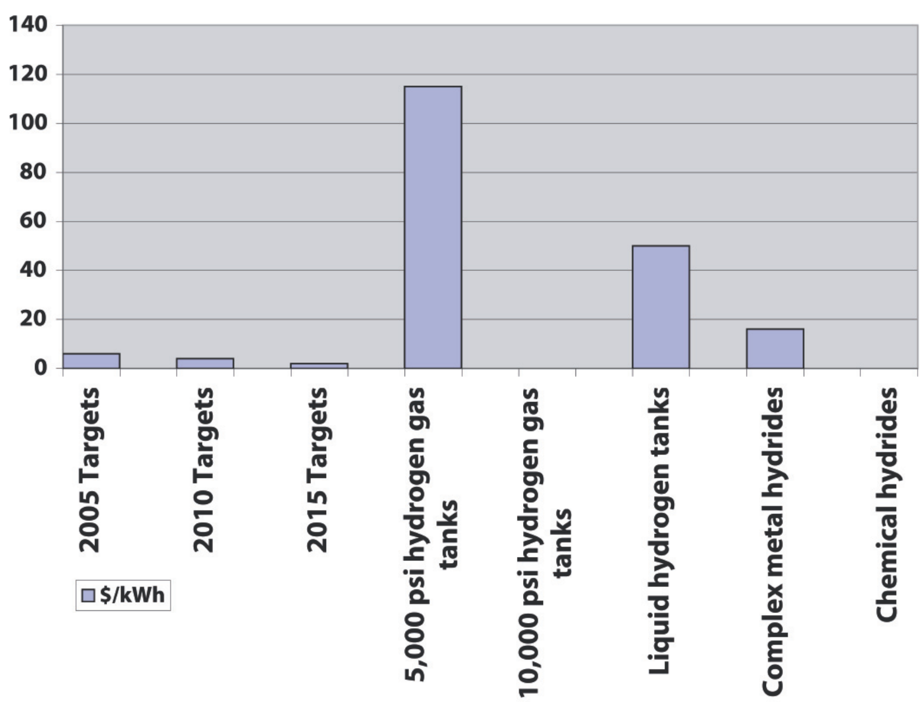


Figure 3.3.4. Status of current technologies relative to the cost targets.



3.3.4.2.1 On-Board Hydrogen Storage Barriers

General

A. Cost. The cost of on-board hydrogen storage systems is too high, particularly compared to conventional storage systems for petroleum fuels. Low-cost materials and components for hydrogen storage systems are needed, as well as low-cost, high-volume manufacturing methods.

B. Weight and Volume. The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate vehicle range compared to conventional petroleum-fueled vehicles. Materials and components are needed that allow compact, lightweight, hydrogen storage systems while enabling greater than 300-mile range in all light-duty vehicle platforms.

C. Efficiency. Energy efficiency is a challenge for all hydrogen storage approaches. For reversible solid-state materials, the energy required to move hydrogen in and out is an issue. Lifecycle energy efficiency is a challenge for chemical hydride storage in which the by-product is regenerated off-board. In addition, the energy associated with compression and liquefaction must be considered for compressed and liquid hydrogen technologies.

D. Durability. Durability of hydrogen storage systems is inadequate to meet automobile manufacturer's requirements. Materials and components are needed that allow hydrogen storage systems with a lifetime of 1500 cycles.

E. Refueling Time. Refueling times are too long. Hydrogen storage systems with refueling times of three to five minutes, over the lifetime of the system, need to be developed.

F. Codes and Standards. Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and ensure safety and public acceptance, have not been established. Standardized hardware and operating procedures, and applicable codes and standards, are required.

G. Life Cycle and Efficiency Analyses. There are no analyses of the full life cycle cost and efficiency for hydrogen storage systems.

Compressed Gas Systems

H. Sufficient Fuel Storage for Acceptable Vehicle Range. Compressed hydrogen storage systems that contain enough hydrogen to provide a range equivalent to conventional vehicles are too bulky, which compromises passenger and luggage space.

I. Materials. High-pressure containment limits the choice of construction materials and fabrication techniques, within the weight, volume, performance, and cost constraints. Research into new materials such as metal ceramic composites, improved resins, and engineered fibers is needed.

J. Lack of Tank Performance Data. An understanding of the fundamental mechanisms that govern composite tank operating cycle life and failures due to accident or neglect is lacking. Data on tank performance and failure are needed to optimize tank structure for performance and cost. An independent test facility is needed that has the capability to acquire the required data.

K. Balance-of-Plant (BOP) Components. Lightweight, cost-effective, high-pressure BOP components are lacking. These include tubing, fittings, check valves, regulators, filters, relief and shutoff valves, and sensors. Sensors to monitor operating parameters such as temperature and pressure as well as those that monitor the condition of "smart" tanks are needed.

Cryogenic Liquid Systems

L. Hydrogen Boil-Off. The boil-off of liquid hydrogen requires venting and presents an energy penalty and a potential safety hazard, particularly in an enclosed environment. Materials and methods to reduce boil-off in cryogenic tanks are needed.

Reversible Solid-State Material Storage Systems (Regenerated On-Board)

M. Hydrogen Capacity and Reversibility. Hydrogen capacity and reversibility are inadequate at practical operating temperatures and pressures and within refueling time constraints. Adequate cycle life of these systems has not been demonstrated.

N. Lack of Understanding of Hydrogen Physisorption and Chemisorption. Fundamental understanding of hydrogen physisorption and chemisorption processes is lacking. Improved understanding and optimization of absorption/desorption kinetics is needed to optimize hydrogen uptake and release.

O. Test Protocols and Evaluation Facilities. Standard test protocols and independent facilities for evaluation of hydrogen storage materials are lacking.

P. Dispensing Technology. Dispensing technology has not been defined.

Chemical Hydride Storage Systems (Regenerated Off-Board)

Q. Regeneration Processes for Irreversible Systems. Low-cost, energy-efficient regeneration processes for irreversible systems have not been established. Cost-effective regeneration processes need to be identified and developed. Full life cycle analyses need to be performed to understand cost, efficiency, and environmental impacts.

R. By-Product Removal. The refueling process is potentially complicated by byproduct removal. System designs must be developed to address the byproduct issue. Additionally, by-product heat removal will need to be addressed. Excess heat can be produced due to the heat of reaction.

3.3.4.2.2 Off-Board Hydrogen Storage Barriers

S. Cost. Lower cost components and containment methods are needed for hydrogen storage. Lower cost compressors and liquefaction methods, which are being addressed by the Hydrogen Delivery program element (see Section 3.2), are also needed.

T. Efficiency. Energy efficiency is a challenge for compression and liquefaction. More efficient compressor designs and liquefiers are needed (see Section 3.2), as well as novel methods of underground storage to reduce diffusion of hydrogen gas and aboveground storage to reduce venting and boil-off losses.

U. Codes and Standards. Applicable codes and standards are needed to facilitate provision of off-board storage at service stations and upstream in the hydrogen supply chain. Without those codes and standards, production facilities must be sized for larger-than-anticipated demand, resulting in increased cost. Standards for hardware and operating procedures to handle venting and boil-off losses are required.

V. Life Cycle and Efficiency Analyses. Systems analyses are needed to determine the full life cycle cost and efficiency for the entire hydrogen production/delivery system. Such studies should look at the cost and performance of each component in the system.

W. Materials. Like on-board tanks, off-board storage tanks required at service stations and other points upstream in the supply chain will have constraints imposed by high-pressure and/or cryogenic containment. A better understanding of the fundamental mechanisms that govern composite tank operating cycle life is needed. Research into new materials such as metal ceramic composites, improved resins, and engineered fibers is needed.

X. Lack of Underground Storage Performance Data. Bulk underground storage is routinely used to provide seasonal and surge capacity for natural gas and may be required for certain hydrogen production/delivery configurations. Novel approaches are needed to deal with the higher diffusion of hydrogen, as compared to natural gas, and to reduce the cost of storage field development. Options such as alternative cushion gases coupled with membrane-separation of recovered hydrogen and identification of geologic structures with particularly promising permeability characteristics need to be examined. Data on diffusion are needed to optimize structure performance and cost. For underground tank storage, an independent test facility is needed that has the capability to acquire the required data.

Y. Hydrogen Boil-Off. The boil-off of liquid hydrogen requires venting and presents an energy penalty and a potential safety hazard. Materials and methods to reduce boil-off in cryogenic tanks in off-board applications are needed.

3.3.4.2.3 Vehicle Interface Barriers

Technical and cost barriers for vehicle interface technologies will be defined in FY 2004.

3.3.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.3.3. Issues regarding safety and environmental effects will be addressed within each of the tasks in coordination with the appropriate program element. For each task, the barriers associated with the task and duration of the task are also listed.

Table 3.3.3. Technical Task Descriptions

Task	Description	Barriers
1	**Compressed and Cryogenic Tanks Meeting 2005 Targets** • Develop, demonstrate, and verify low-cost, compact 10,000-psi storage tanks. • Develop liner materials and fabrication processes to reduce hydrogen gas permeation. • Develop and optimize carbon fiber/epoxy overwrap. • Identify alternative designs and materials for advanced, integrated storage systems. • Explore conformable tanks for compressed hydrogen. • Technically demonstrate safety of hydrogen storage systems. • Explore compressed gas/reversible storage material hybrid systems. • Characterize failure modes in composite tanks and develop early warning sensors to predict potential failure in smart tanks. • Establish an independent test facility to acquire data on performance and durability of compressed tanks using standardized test methods. • Develop "smart tank" technologies that allow complete and rapid refueling within material temperature constraints. • Develop technologies to accurately sense and meter high-pressure hydrogen. • Develop lightweight, low-cost balance of plant components for compressed and cryogenic tanks. • Develop and demonstrate low cost, insulated pressure vessels for cryogenic hydrogen storage with reduced evaporative losses. • Analyze and perform a comparative assessment of physical storage systems for their ability to achieve 2010 weight and volume goals, including an evaluation of alternative designs, operations, fuel and infrastructure costs, and energy issues. • Study requirements and conceptual designs for cost-competitive off-board storage of hydrogen, including underground scenarios.	12 Quarters/Barriers A-L
2	**Advanced Compressed and Cryogenic Tank Technologies** • Develop advanced compressed and cryogenic tank technologies to meet 2010 targets.	12 Quarters/Barriers A-L

3	**Reversible Solid-State Hydrogen Storage Materials R&D (Regenerated On-Board) Meeting 2005 Targets** • Perform theoretical modeling to provide guidance for materials development. • Improve understanding of sodium alanate system to aid development of alanate materials with higher hydrogen capacities. • Investigate a family of alanate materials with hydrogen capacities of 6 wt% or greater with adequate kinetics and cycling characteristics. • Investigate composite-wall containers compatible with the optimal alanate materials. • Determine the decomposition products and pathways of materials to better understand their mechanisms and kinetics. • Engineer a hydride bed capable of efficiently storing and releasing hydrogen at 90°C. • Determine the hydrogen storage capacity of nanostructured carbon materials. • Develop cost-effective fabrication processes for promising nanostructured carbon materials. • Explore combinatorial approaches to speed the identification of promising hydrogen storage materials. • Perform analyses to assess cost effectiveness of reversible hydrogen storage materials including scaleup to high-volume production. • Explore nonthermal discharging methods, including mechanical, chemical, and electrical mechanisms. • Establish an independent test facility and standard test protocols to evaluate reversible hydrogen storage materials.	12 Quarters/Barriers A-G, M-P
4	**Advanced Reversible Solid-State Materials** • Develop and verify most promising reversible storage materials to meet 2010 targets.	12 Quarters/Barriers A-G, M-P
5	**Advanced Reversible Solid-State Materials** • Develop and verify most promising reversible storage materials to meet 2015 targets.	20 Quarters/Barriers A-G, M-P

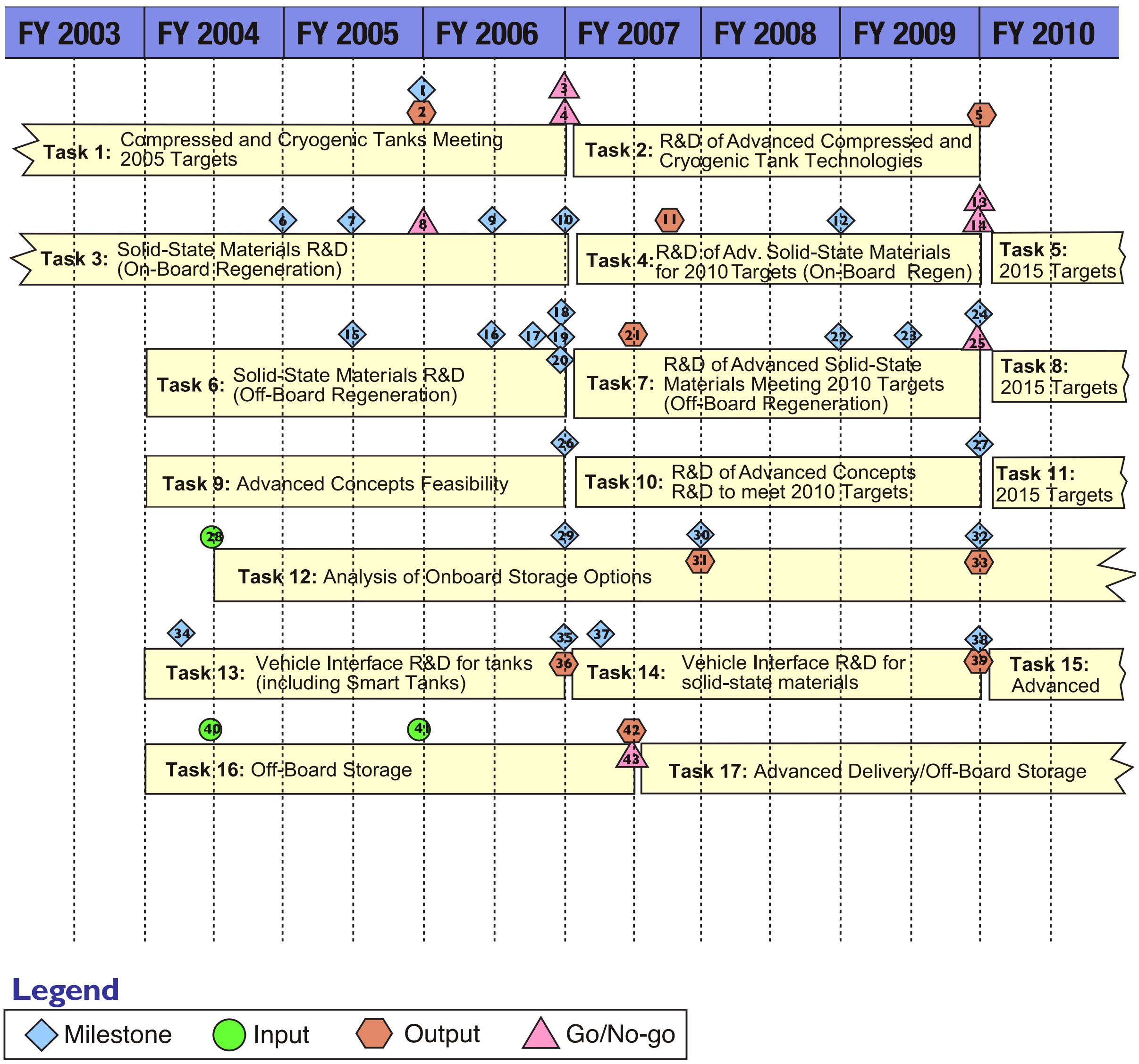
6	**Chemical Hydride Storage (Off-Board Regeneration)** • Identify a family of hydrolysis hydride storage materials capable of meeting weight and volume goals. Characterize the reaction chemistry and thermodynamics of the most promising candidates. • Rank viable candidates according to hydrogen capacity based on resource availability, full fuel cycle energy efficiency and emissions, and cost of the delivered fuel. • Identify and develop improved processes, chemistry, catalysts, and operating conditions for the complete fuel cycle. • Evaluate the safety performance of the complete system. • Verify an entire closed-loop, hydrolysis hydride storage system, including an efficient regeneration process that meets cost and performance targets. • Develop applicable codes and standards for on-vehicle storage and fueling interface. • Assess the impact of a potentially complicated refueling process (due to by-product removal) on implementation of irreversible hydrogen storage systems.	12 Quarters/Barriers A-G, Q, R
7	**Advanced Chemical Hydride Storage (Off-Board Regeneration)** • Develop and verify most promising reversible storage materials to meet 2010 targets.	12 Quarters/Barriers A-G, Q, R
8	**Advanced Chemical Hydride Storage (Off-Board Regeneration)** • Develop and verify most promising reversible storage materials to meet 2015 targets.	20 Quarters/Barriers A-G, Q, R
9	**Advanced Concepts Feasibility** • Identify and investigate advanced reversible material storage approaches that have the potential to achieve 2010 targets of 2 kWh/kg (6 wt%) or greater, and 1.5 kWh/L or greater.	12 Quarters/Barriers A-G
10	**Advanced Concepts R&D** • Develop and characterize advanced hydrogen storage concepts to meet 2010 targets.	12 Quarters/Barriers A-G
11	**Advanced Concepts R&D** • Develop and characterize advanced hydrogen storage concepts to meet 2015 targets.	20 Quarters/Barriers A-G

12	**Analysis of On-Board Storage Options** • Conduct analyses to examine cost and energy efficiency of the technologies developed, changes in the system level requirements that might alter the technical targets, and progress of each technology development effort toward achieving the technical targets.	42 Quarters/Barriers A-G
13	**Vehicle Interface R&D – Compressed and Liquid Tank** • Fabricate and verify the performance of vehicle refueling connection devices based on SAE International Surface Vehicle Standard J2600 at working pressures of 5,000 psi. • Design, develop, and test vehicle refueling connection devices that allow working pressures of 5,000 psi to 10,000 psi. • Explore the requirements of vehicle refueling connection devices for hydrogen storage systems based on reversible and irreversible materials. • Develop software control systems for fast refueling of on-board hydrogen storage systems. • Develop and verify “smart tank” concepts.	12 Quarters/Barriers E, F, J
14	**Vehicle Interface R&D – Materials** • Develop and verify vehicle interface technologies for hydrogen storage systems based on solid-state materials to meet 2010 targets.	12 Quarters/Barriers E, F, J
15	**Vehicle Interface R&D - Advanced Materials Systems** • Develop and verify vehicle interface technologies for hydrogen storage systems based on advanced solid-state materials to meet 2015 targets.	20 Quarters/Barriers E, F, J
16	**Off-Board Hydrogen Storage** • Conduct an assessment of the R&D requirements for off-board storage. • Initiate R&D of off-board storage technologies. • Downselect off-board storage technologies.	12 Quarters/Barriers S-Y
17	**Advanced Off-Board Hydrogen Storage** • Continue R&D of advanced off-board storage technologies	32 Quarters/Barriers S-Y

3.3.6 Milestones

Figure 3.3.5 shows the interrelationship of milestones, tasks, supporting inputs from other program elements, and technology program outputs for the Hydrogen Storage program element from FY 2004 through FY 2010. This information is also presented in Table B.3 in Appendix B.

Figure 3.3.5. Hydrogen Storage R&D Network



For chart details see next page.

1. Complete feasibility study of hybrid tank concepts.
2. Output to Technology Validation: Compressed and cryogenic liquid storage tanks achieving the 2005 targets
3. Go/No-Go: Decision on insulated pressure vessels for cryogenic tanks with minimum evaporative losses
4. Go/No-Go: Decision on liquid and compressed tank technologies
5. Output to Technology Validation: Advanced compressed/cryogenic tank technologies; End tank R&D
6. Complete construction of materials test facility.
7. Complete verification of test facility.
8. Go/No-Go: Decision point on carbon nanotubes
9. Complete prototype complex hydride integrated system meeting 2005 targets.
10. Downselect complex hydride materials.
11. Output to Technology Validation and Fuel Cells: Complex hydride integrated system meeting 2005 targets
12. Complete prototype complex hydride integrated system meeting 2010 targets.
13. Go/No-Go: Decision on continuation of complex hydride R&D
14. Go/No-Go: Decision point on other carbon nanostructures
15. Downselect from hydride regeneration processes.
16. Demonstrate efficient hydride regeneration laboratory process.
17. Complete chemical hydride life-cycle analysis.
18. Demonstrate scaled-up hydride regeneration process.
19. Complete prototype hydride integrated system.
20. Downselect from chemical storage approaches for 2010 targets.
21. Output to Technology Validation and Fuel Cells: Full-cycle, integrated chemical hydride system meeting 2005 targets
22. Demonstrate advanced hydride regeneration laboratory process.
23. Complete prototype advanced chemical storage integrated system.
24. Demonstrate scaled-up advanced hydride regeneration process.
25. Go/No-Go: Decision point on chemical storage R&D for 2015 targets
26. Downselect from advanced concepts.
27. Downselect the two most promising advanced concepts for continued development.
28. Input from Safety: Safety requirements and protocols for on-board storage
29. Update on-board storage targets.
30. Complete analysis of best storage option for 2010 targets.
31. Output to Hydrogen Delivery: Initial downselect of on-board storage system
32. Complete analysis of best storage option for 2015 targets.
33. Output to Hydrogen Delivery: Final downselect of on-board storage system
34. Complete assessment of vehicle interface technology needs for compressed and liquid tanks.
35. Downselect from “smart tank” technologies.
36. Output to Technology Validation: Vehicle interface technology
37. Complete assessment of vehicle interface technology needs for advanced materials storage systems
38. Downselect vehicle interface technology needs for advanced materials storage systems.
39. Output to Technology Validation: Vehicle interface technology
40. Input from Safety: Safety requirements/protocols for bulk storage
41. Input from Hydrogen Delivery: Assessment of cost-competitive off-board storage requirements
42. Output to Technology Validation and Hydrogen Delivery: Bulk off-board storage technology for fueling stations and delivery
43. Go/No-Go: Decision on continued R&D for off-board storage